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Assessing Exposure Metrics for PM and Birthweight Models

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Abstract

The link between air pollution exposure and adverse birth outcomes is of public health concern due to the relationship between poor pregnancy outcomes and the onset of childhood and adult diseases. As personal exposure measurements are difficult and expensive to obtain, proximate measures of air pollution exposure are traditionally used. We explored how different air pollution exposure metrics affect birthweight regression models. We examined the effect of maternal exposure to ambient levels of particulate matter <10, <2.5 μm in aerodynamic diameter (PM_{10}, $PM_{2.5}$) on birthweight among infants in North Carolina. We linked maternal residence to the closest monitor during pregnancy for 2000–2002 (n=350,754). County-level averages of air pollution concentrations were estimated for the entire pregnancy and each trimester. For a finer spatially resolved metric, we calculated exposure averages for women living within 20, 10, and 5 km of a monitor. Multiple linear regression was used to determine the association between exposure and birthweight, adjusting for standard covariates. In the county level model, an interquartile increase in PM_{10} and $PM_{2.5}$ during the entire gestational period reduced birthweight by 5.3 g (95% CI: 3.3 – 7.4) and 4.6 g (95% CI: 2.3 – 6.8), respectively. This model also showed a reduction in birthweight for PM_{10} (7.1 g, 95% CI: 1.0–13.2) and $PM_{2.5}$ (10.4 g, 95% CI: 6.4 – 14.4) during the third trimester. Proximity models for 20, 10, and 5 km distances showed similar results to the county level models. County level models assume that exposure is spatially homogeneous over a larger surface area than proximity models. Sensitivity analysis demonstrated that at varying spatial resolutions, there is still a stable and negative association between air pollution and birthweight, despite North Carolina's consistent attainment of federal air quality standards.

Keywords

air pollution; particulate matter; birthweight; birth outcomes; exposure metrics

INTRODUCTION

Many epidemiological studies have been conducted to investigate the effect of maternal exposure to air pollution on adverse pregnancy outcomes (1–5). Results of these studies have shown that exposure to air pollution may elevate the risk of adverse birth outcomes, including low birthweight, preterm delivery, and small for gestational age (6–12).

Poor birth outcomes are significant predictors of neonatal mortality and morbidity (13). Evidence shows that children born low birthweight, preterm delivery, or small for gestational age are at an increased risk for both short-term neonatal morbidity and long-term health effects (14,15). Such effects include mental retardation (16), severe vision loss (17), deafness (16),

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learning disabilities (18,19), motor impairment (20), and cerebral palsy (21), as well as hypertension, cardiovascular disease, and type-2 diabetes in adulthood (22).

Although the biological mechanisms by which air pollutants may influence birthweight and fetal growth are as yet unknown, studies suggest that air pollution exposure during pregnancy may lead to placental inflammation, which impairs placental function, and chronic inflammation may in turn result in growth restriction (6). Data also suggest that fetuses may be more prone to genetic damage and process toxicants less efficiently than adults (23). Perera et al. (24) also propose that increased DNA adducts in the fetus relative to the mother could result in lower levels of detoxification enzymes and decreased DNA repair efficiency in the fetus.

Epidemiologists and policy makers are often interested in the effect of particulate air pollution on susceptible populations (25); thus pregnant women are of particular concern. Since the National Research Council (NRC) identified at risk subpopulations as a high priority research task, several studies have been conducted to better examine the effects of PM exposure and adverse pregnancy outcomes (1,26,27). In the last of four reports produced by the NRC in 2004, the group determined that more research needs to be done in order to clarify uncertainties about impacts of maternal exposure to PM on pregnancy and to understand how environmental factors can affect adverse pregnancy outcomes (28).

While much attention has been given to studying the relationship between adverse pregnancy outcomes and air pollution, many of these studies are limited to sparsely located monitoring station data (1,2,29). These studies use average measurements calculated from monitoring stations within city or county limits, or postal codes. Epidemiologists are aware that measurements obtained from ambient monitoring stations may not be representative of personal exposure for all subjects within a predetermined geographic area (30). Consequently, the use of personal exposure measures based on city or county levels may misclassify individual exposure.

Although many studies have found significant results, the traditional analyses may misclassify exposure because of the way the exposure is measured and modeled (31,32). Using measurements based on residing either within a certain geographic area or proximity to a monitoring station as a proxy for personal exposure assumes that air pollution levels are spatially homogeneous across the defined geographic regions. While lacking precision, this method of estimating exposure for an individual or a population has been used in air pollution and health effects studies (33–35) as collection of accurate personal level exposures is often difficult and expensive to obtain. In the presence of potential measurement error, it is important to determine whether these various measurements affect the exposure-response relationship.

In this paper, we evaluate how robust the air pollution and birthweight relationship is to different air pollution measurements. For comparability to other studies (1,3,36), we use air pollution metrics based on county averages for the State of North Carolina. We then use buffering schemes associated with proximity models of 20, 10 and 5 km radii and compare how these different exposure metrics affect the birthweight model. Because previous studies have used distances ranging from 2 km to 50 km (37–39), we chose a range of distances for greater cross-study comparability. Our goal is to investigate how birthweight regression models change when different exposure metrics are used. Importantly, North Carolina communities are typically below the federal standards for both PM_{10} and $PM_{2.5}$, so these analyses have direct relevance to the policy debate regarding setting regulatory standards to protect public health.

METHODS

Birth Data

The North Carolina Detailed Birth Record (NCDBR) data were obtained from the North Carolina State Center for Health Statistics. The NCDBR data contain information on both birth outcomes and parental demographics for all registered births in North Carolina. We limited our analysis to the years 2000–2002 (n=350,754). The recorded birth information in the NCDBR used in this study included gestational age (weeks), infant sex, birthweight, congenital anomalies, and year of birth. The maternal characteristics recorded in the NCDBR included residential address, age, marital status, education, race and ethnicity, alcohol and tobacco use, plurality, birth order, and the trimester in which prenatal care began.

To link births from the NCDBR to the air pollution data, we used ArcGIS software to street geocode the residential addresses in the dataset at the individual record level. The total births successfully geocoded using the maternal residence at the time of delivery in North Carolina can be seen in Figure 1. Approximately 17% of the total births could not be geocoded due to unmatched address locations. To determine whether systematic differences exist between the full geocoded dataset and the subsets for which air pollution data were available, summary statistics (data not shown) were calculated using Census data from the zip code links and the DBR data. Differences were not significant enough to undermine the analytical work presented here.

We excluded multi-fetal births (3.3%), and infants characterized by congenital anomalies (0.9%). These exclusions were chosen as we sought to focus on those pregnancies that could reasonably be expected to go to term and deliver at a normal birthweight. We also excluded women < 15 and > 44 years (0.3%) with reported alcohol consumption (0.6%). Since 95% of the women in the dataset self-declared as non-Hispanic white, non-Hispanic black, or Hispanic, we excluded other races/ethnicities due to the small sample size for other minority groups. We excluded births with gestation <32 and >44 weeks (2.2%), birthweight <1000g and >5500g (1.0%), impossible birthweight and gestation combinations (0.1%) (Alexander et al., 1996), and mothers with any missing data on covariates (1.0%), leaving 259,962 cases. For the county level model, we focused on women who lived in a county with an active monitoring station while for the proximity models, we used only women within a 20, 10, and 5 km buffer of a monitoring station.

Air Pollution Data

The air pollution datasets for PM_{10} and $PM_{2.5}$ were obtained from the US EPA Air Quality System (AQS) for 1999–2002 (40). The analyses used births between the years of 2000–2002, and air pollution exposures from 1999–2002, since exposures for some 2000 births occurred in 1999. The AQS data contained the daily 24-hr average concentration ($\mu g/m^3$) for PM_{10} and $PM_{2.5}$. There were between 27 and 37 active PM_{10} monitors and between 37 and 41 active $PM_{2.5}$ monitors in North Carolina during 1999–2002. The monitors recorded pollution measurements every day, every 3 days, or every six days with some monitors being added to or removed from operation during the years of the study. The difference in the frequency of recordings at certain monitoring stations is random and should not introduce any bias into the study. Locations of the PM_{10} and $PM_{2.5}$ monitors in North Carolina can be seen in Figure 2.

Maternal Exposure Assessment

To estimate air pollution exposure for the proximity models, each mother's residence at the time of delivery was linked to the closest active monitor. The weeks of exposure were calculated based on the actual weeks of pregnancy as recorded in the NCDBR. Since birth date and gestational age were supplied as part of the NCDBR data, we calculated backwards the number of weeks of gestation from the delivery date to determine an estimated date of conception for each woman. Average maternal exposure was calculated for each pollutant by averaging the daily or weekly data of the closest monitoring station for each trimester. Trimesters were constructed based on the following categorization: 1–13 weeks of gestation, 14–26 weeks of gestations, and 27 weeks of gestation until birth. Exposure estimates averaged over the entire pregnancy were also calculated for each pollutant.

AQS data were not available for every day and week of the years 1999–2002. For each birth, the completeness of the exposure dataset was identified by taking the number of weeks of gestation and dividing it by the number of AQS concentration values for that birth. If the birth had more than 75% of the data and there was no more than one consecutive missing concentration value for that birth, then the average of the concentrations for the weeks before and after the missing value were used as a proxy for the exposure concentration during that week. If there was more than one consecutive missing value for a birth, then that birth was not included in the dataset because a sufficient proxy for the two weeks or more of missing air quality data was not available. After all exclusion criteria, exposure estimates were calculated for 195,141 mothers for at least one of the pollutants of interest.

Statistical Analysis

Multiple linear regression modeling was used to determine the association between exposure to the pollutants of interest, PM_{10} and $PM_{2.5}$, and birthweight. Using birthweight as a continuous outcome variable, we controlled for gestational age (32–34, 35–35, 37–38, 39–40, 41–42, 43–44 weeks), maternal race/ethnicity (non-Hispanic black, non-Hispanic white, or Hispanic), maternal education (< 9, 9–11, 12, 13–15, > 15 years), maternal age (15–19, 20–24, 25–29, 30–34, 35–39, 40–44 years), trimester prenatal care began, tobacco use during pregnancy (yes or no), marital status (married or unmarried), year of birth, firstborn (yes or no), and infant sex (male or female) for PM_{10} and $PM_{2.5}$. The exposure estimates were considered as continuous variables. We then examined the exposure response relationship with county-wide estimates and estimates for mothers within 20, 10 and 5 km of a monitoring station.

A baseline model without the air pollution variables was constructed to examine which of the standard covariates mentioned above affect birthweight in our sample. We then constructed separate models for PM_{10} and $PM_{2.5}$. For comparability to previous studies, we constructed models using all three trimester exposure estimates in the same model as well as models with a pregnancy-long estimate (41–43). All risk factors considered were observed as being associated with birthweight in recent literature (1,2,4,44,45).

RESULTS

Our analysis included estimating pollution exposures for sample populations at the county level, and within the 20, 10 and 5 km radial buffers surrounding monitors. At the county level, there were 195,141 observations with the restrictions described above and 167,851, 110,555, and 56,043 births at 20, 10 and 5 km, respectively. Table 1 shows the summary statistics for each of the four sample populations (county and 20, 10, and 5 km buffers). Among the 195,141 county-level births, the mean birthweight was 3,368 g and the prevalence of low birthweight was 5.4%. Approximately 11% reported smoking during pregnancy. Most of the mothers were non-Hispanic white (61%), married (68%), and with more than a high school education (52.8%). The mean PM_{10} and $PM_{2.5}$ levels are higher than the median, a phenomenon driven by a few geographic areas with higher pollution levels (e.g., the greater Charlotte area).

The descriptive characteristics of the mothers living within 20 and 10 km of a monitoring station are similar to those in the county level dataset. Some maternal demographics change with proximity to the monitoring station, including maternal race/ethnicity, maternal education,

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and marital status. Moving from 20 km away to 5 km away from a monitoring station increases the non-Hispanic black population by approximately 14% and Hispanic population by 6.2%. There is also a decrease in the mothers with more than a high school education, as well as those who are married, as residence gets closer to a monitor. The incidence of LBW increases from 5.2% at 20 km to 6.3% at the 5 km buffer. The means ± standard deviations (SD) along with the interquartile range (IQR) and 25th, 50th and 75th percentiles of the average exposure of each pollutant are shown in Table 2 for the county and 20 km models. Summary statistics of the pollution averages for the 10 and 5 km models (not shown) were similar to the results at the 20 km level. For the 10 km buffer there were 75,111 and 86,573 observations for PM_{10} and $PM_{2.5}$ respectively. At the 5 km level there were 35,212 and 42,782 observations for PM_{10} and $PM_{2.5}$ respectively.

Average values of PM_{10} ($PM_{2.5}$) concentration levels were approximately 22.7 (14.3) μg/m^3. The $PM_{2.5}$ average is below the National Ambient Air Quality Standard (NAAQS) annual mean of 15 μg/m^3 and there is currently no annual PM_{10} standard. The correlations between PM_{10} and $PM_{2.5}$ during each trimester remain relatively consistent with r^2 ~0.7. The correlation between PM_{10} and $PM_{2.5}$ exposure during the entire pregnancy was 0.63. Table 3 shows the correlation coefficients among trimester exposures for PM_{10} and $PM_{2.5}$ at the county level model. Similar correlations were obtained at the 20, 10, and 5 km level.

In all of the baseline models with no air pollution estimates, the standard covariates carried the expected signs with positive correlation between birthweight and longer gestation (>40 weeks), male sex, more than a high school level education and higher parity; and negative correlation between birthweight and tobacco use during pregnancy, unmarried status, less than high school education, minority race groups, firstborns, mothers younger than 24 years and older than 40 years, and mothers who started prenatal care later in pregnancy. All covariates were statistically significant ($p<.001$) and were included in the models with pollution estimates. Table 4 shows the baseline models for PM_{10} at the county level and the 20 km level. Similar results (not shown) were obtained for both pollutants at the county level and the 20, 10, and 5 km buffer levels.

In the multiple regression models for the county level measure of air pollution exposure, PM_{10} and $PM_{2.5}$ exposure in the third trimester and during the entire pregnancy were negatively associated with birthweight (Figure 3). An IQR increase in PM_{10} and $PM_{2.5}$ during the entire gestational period reduced birthweight by 5.3 g [95% CI, 3.3 – 7.4] and 4.6 g (95% CI, 2.3 – 6.8) respectively. This model also showed a reduction in birthweight for PM_{10} (7.1 g, 95% CI=1.0–13.2) and $PM_{2.5}$ (10.4 g, 95% CI= 6.4 – 14.4) during the third trimester.

Proximity models for 20, 10, and 5 km distances showed results similar to the county level models (Figure 3). During the entire gestational period, there were birthweight reductions between 7 and 8 g for PM_{10} and 7 and 10 g for $PM_{2.5}$ per IQR increase in each pollutant. Exposure during the third trimester also showed significant results similar to the county level models for both pollutants. $PM_{2.5}$ showed birthweight reductions at 20 and 10 km but not 5 km or the county level model. We also ran logistic models to see whether air pollution exposure predicted low birthweight or very low birthweight (results not shown here). The only statistically significant results were for pregnancy-long $PM_{2.5}$ exposure and the odds ratios were very close to one.

DISCUSSION

County level models assume that air pollution exposure is spatially homogeneous over a larger surface area than city-wide or neighborhood level models. If air pollution concentrations are heterogeneous, with variability that increases as distance from the pollution source increases, then the associated measurement error may also be larger in exposure measurements based on large geographic regions. This misclassification in the pollution concentration could underestimate the true effects of air pollution exposure. For this reason, we explored the relationship between both county and neighborhood level averages of PM. This sensitivity analysis compared birthweight regression results using exposure metrics for PM_{10} and $PM_{2.5}$ at various spatial resolutions from 2000–2002 in North Carolina. We observe some differences in both the magnitude of the coefficients and the significance of the estimates as well. The model for the entire gestational period showed both significant and negative associations for PM_{10} and $PM_{2.5}$ with all the exposure metrics used.

Basu et al. (46) explore the use of different spatial measures of exposure in birthweight regression models and also found differences between the various metrics in a study in California in 2000. Basu et al. found that county level measures of $PM_{2.5}$ produced a stronger reduction in birthweight than exposure measures within a 5-mile radius of a monitoring station. This California study limited analysis to non-Hispanic white and Hispanic mothers in California, where air pollution levels are relatively high compared to North Carolina. Although there are differences in the demographic composition and the air pollution levels, similar results were seen when comparing county-level models to proximity models.

In another study using data from Connecticut and Massachusetts, Bell et al. (1) saw reductions in birthweight at the county level during the entire pregnancy and the third trimester for both PM_{10} and $PM_{2.5}$, which is consistent with the results in our study. This study had average PM levels similar to those in NC, with means of 22.3 and 11.9 $\mu g/m^3$ for PM_{10} and $PM_{2.5}$, respectively. Comparable results in the reduction of birthweight per IQR increase in PM_{10} and $PM_{2.5}$ were seen in the North Carolina county level models and the models presented in the Bell et al. analysis.

Other studies have also found an inverse relationship between exposure to PM and reduction in birthweight, using both county level and neighborhood level exposure metrics. Dugandzic et al. (4), Gouveia et al. (47), and Yang et al. (37) all found a significant relationship in the first trimester for PM_{10} exposure and birthweight in a study in Taiwan, Canada and Brazil respectively. Salam et al. (43) in a California study found that exposure to PM_{10} during the 3rd trimester was negatively associated with birthweight. Mannes et al. (39) showed in a study in Australia that both PM_{10} and $PM_{2.5}$ were associated with reduced birthweight during the second trimester as well as during the last month of pregnancy. In California, Parker et al. (48) found a negative effect of $PM_{2.5}$ on birthweight for all three trimesters when comparing the highest and lowest levels of $PM_{2.5}$. It is still unclear which exposure period is most affected and further analysis is certainly needed.

A limitation to this research is the quantity and placement of active PM monitoring sites each year. Monitoring sites are part of a long-term fixed network that was established for regulatory purposes, rather than for health effects research. In some geographic areas, such as those closer to major cities and roadways, there is a greater density of monitors. Monitoring data from these areas are more representative of ambient maternal exposures than in areas where the monitors were more distal from maternal residences. Thus, the exposures of women who lived in more urban areas were more accurately captured than those women who were at the far range of the 20 km buffer set for this study. Additionally, individual exposure measurements calculated using ambient concentrations readings from monitoring stations introduce misclassification errors into the study. Without using personal monitors, one cannot truly capture actual exposure.

We also make the assumption that pregnant women did not relocate during their pregnancy. Other relevant maternal information such as gestational weight gain, maternal nutrition, and

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indoor and occupational exposure estimates are factors that may affect birthweight but could not be examined. In addition, use of assisted reproductive technology, even among singleton pregnancies, is a known risk factor for PTB (49), but cannot be controlled for in our analyses (data not available).

This study examined only PM_{10} and $PM_{2.5}$ which are highly correlated with each other and possibly with other pollutants. The PM_{10} monitors used in this study also measure ambient levels of $PM_{2.5}$. Consequently, the lower birthweight associated with PM_{10} may in fact be indistinguishable from the birthweight effects attributable to $PM_{2.5}$. To address this issue, the EPA's Clean Air Scientific Advisory Committee has recommended that the Agency develop a new indicator for particles between 2.5 and 10 micrometers in diameter ($PM_{2.5–10}$) because PM_{10} sampling is an imprecise measure of coarse particulate matter in this size range (50). At present, there is inadequate information on $PM_{2.5–10}$ ambient levels, exposure, and health risks. In the October 2006 revision to the PM NAAQS, however, EPA retained PM_{10} as the indicator for coarse particles.

In North Carolina, the annual NAAQS for $PM_{2.5}$ is 15.0 $\mu g/m^3$ averaged over a three-year period for each monitor (51). In October 2006, the EPA rescinded the 50 $\mu g/m^3$ annual standard for PM_{10}, citing a lack of association between long-term exposure to current ambient levels of PM_{10} and adverse health effects. Consequently, there is currently no annual standard for PM_{10}. Although average annual $PM_{2.5}$ levels in North Carolina are less than the standard of 15 $\mu g/m^3$, we still see robust relationships between $PM_{2.5}$ exposure and birthweight. Similarly, PM_{10} levels are less than half of the previous NAAQS of 50 $\mu g/m^3$, yet maternal exposure to PM_{10}, both during the third trimester and during the entire pregnancy, is negatively associated with birthweight. While our results show a small reduction in birthweight for the entire pregnancy across both pollutants, average county levels of PM_{10} and $PM_{2.5}$ (22.7, 14.3) were associated with a reduction in mean birthweight of 25.1 g (95% CI: 20.2 – 29.9) and 41.0 g (95% CI: 30.9 – 51.1), respectively. These reductions are meaningful in North Carolina, and potentially even more so in regions with air quality below the NAAQS.

Exposure to PM pollution during pregnancy is an important public health issue. In our study, the county level model produced consistent results with the proximity model for estimating reductions in birthweight during the entire pregnancy and in the third trimester for both PM_{10} and $PM_{2.5}$. There were some differences in the first trimester for PM_{10} and the second trimester for $PM_{2.5}$. In both cases, there was a reduction in birthweight at the 20 km and 10 km level but not at the county level or the 5 km level.

Our study provides comparability to previous studies by examining the relationship between birthweight and average county levels of PM_{10} and $PM_{2.5}$. In addition, we go beyond the previous studies by constructing proximity models using 20, 10, and 5 km buffers around monitoring stations. These additional analyses indicate that the statistical significance and negative relationship between birthweight and air pollution is robust to the choice of air pollution metrics at substantially different geographic scales. Despite North Carolina's consistent attainment of federal air quality standards, we still see a stable and negative association between both pollutants and birthweight in the third trimester and during the entire pregnancy at various spatial resolutions.

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References

1. Bell ML, Ebisu K, Belanger K. Ambient Air Pollution and Low Birth Weight in Connecticut and Massachusetts . Environ Health Perspect 2007;115(7):1118–1124. [PubMed: 17637932]
2. Bobak M. Outdoor air pollution, low birth weight, and prematurity. Environ Health Perspect 2000;108 (2):173–176. [PubMed: 10656859]
3. Chen L, Yang W, Jennison BL, Goodrich A, Omaye ST. Air Pollution and Birth Weight in Northern Nevada, 1991–1999. Inhal Toxicol 2002;14:141–157. [PubMed: 12122577]
4. Dugandzic R, Dodds L, Stieb D, Smith-Doiron M. The association between low level exposures to ambient air pollution and term low birth weight: a retrospective cohort study. Environmental Health: A Global Access Science Source 2006;5(1):3. [PubMed: 16503975]
5. Ha E-H, Hong Y-C, Lee B-E, Woo B-H, Schwartz J, Christiani DC. Is Air Pollution a Risk Factor for Low Birth Weight in Seoul? Epidemiology 2001;12(6):643–648. [PubMed: 11679791]
6. Lee BHE, Park H, Kim Y, Hong Y, Kim K, Lee J. Exposure to air pollution during different gestational phases contributes to risks of low birth weight . Human Reproduction 2003;18(3):638–643. [PubMed: 12615838]
7. Lin CMLC, Yang CY, Mao IF. Association between maternal exposure to elevated ambient sulfur dioxide during pregnancy and term low birth weight . Environmental Research 2004;96:41–50. [PubMed: 15261783]
8. Parker JDWT, Basu R, Schoendorf KC. Air Pollution and Birth Weight Among Term Infants in California . Pediatrics January;2005 115(1):121–128. [PubMed: 15629991]
9. Yang CYTY, Chang CC. Effects of Air Pollution on Birth Weight Among Children Born between 1995 and 1997 in Kaohsiung, Taiwan. Journal of Toxicology and Environmental Health 2003;66:807–816. [PubMed: 12746128]
10. Vassilev ZPRM. Associations of Polycyclic Organic Matter in Outdoor Air with Decreased Birth Weight: A Pilot Cross-Sectional Analysis. Journal of Toxicology and Environmental Health 2001;64 (Part A):595–605. [PubMed: 11766167]
11. Ritz B, Yu F, Chapa G, Fruin S. Effect of air pollution on preterm birth among children born in Southern California between 1989 and 1993 . Epidemiology 2000;11(5):502–511. [PubMed: 10955401]
12. Mannes T, Jalaludin B, Morgan G, Lincoln D, Sheppeard V, Corbett S. Impact of ambient air pollution on birth weight in Sydney, Australia . Occupational & Environmental Medicine 2005;62:524–530. [PubMed: 16046604]
13. McCormick MC. The Contribution of Low Birth Weight to Infant Mortality and Childhood Morbidity . The New England Journal of Medicine 1985;312(2):82–90. [PubMed: 3880598]
14. Hack MKN, Taylor HG. Long-term developmental outcomes of low birth weight infants . Future Child 1995;5(1):176–196. [PubMed: 7543353]
15. Lemons JABC, Oh W, Korones SB, Papile LA, Stoll BJ, Verter J, Temprosa M, Wright LL, Ehrenkranz RA, Fanaroff AA, Stark A, Carlo W, Tyson JE, Donovan EF, Shankaran S, Stevenson DK. Very low birth weight outcomes of the National Institute of Child Health and Human Development Neonatal Research Network, January 1995 through December 1996. NICHD Neonatal Research Network . Pediatrics 2001;107(1):E1. [PubMed: 11134465]
16. Lorenz JMWD, Jetton JR, Paneth N. A quantitative review of mortality and developmental disability in extremely premature newborns . Arch Pediatr Adolesc Med 1998;152(5):425–435. [PubMed: 9605024]
17. Crofts BJ, King R, Johnson A. The contribution of low birth weight to severe vision loss in a geographically defined population . Br J Ophthalmol 1998;82(1):9–13. [PubMed: 9536872]
18. Resnick MBGR, Carter RL, Ariet M, Sun Y, Roth J, Bucciarelli RL, Curran JS, Mahan CS. The impact of low birth weight, perinatal conditions, and sociodemographic factors on educational outcome in kindergarten . Pediatrics 1999;104(6):e74. [PubMed: 10586008]

19. Saigal SHL, Streiner DL, Stoskopf BL, Rosenbaum PL. School difficulties at adolescence in a regional cohort of children who were extremely low birth weight . Pediatrics 2000;105(2):325–331. [PubMed: 10654950]
20. Ross GLE, Auld PA. Social competence and behavior problems in premature children at school age . Pediatrics 1990;86(3):391–397. [PubMed: 2388788]
21. Kuban KCLA. New England Journal of Medicine. Cerebral Palsy 1994;330(3):188–195.
22. Ashdown-Lambert J. A Review of Low Birth Weight: Predictors, Precursors, and Morbidity Outcomes. The Journal of the Royal Society for the Promotion of Health 2005;125(2):76–83. [PubMed: 15819182]
23. Perera FPJW, Rauh V, Whyatt RM. Molecular Epidemiologic Research on the Effects of Environmental Pollutants on the Fetus . Environmental Health Perspectives June;1999 107(S3):451–460. [PubMed: 10346993]
24. Perera FP, Jedrychowski W, Rauh V, Whyatt RM. Molecular epidemiologic research on the effects of environmental pollutants on the fetus . Environ Health Perspect 1999;107 (Suppl 3):451–460. [PubMed: 10346993]
25. NRC. Research Priorities for Airborne Particulate Matter, I: Immediate Priorities in a Long-Range Research Portfolio. National Academy Press; Washington, DC: 1998.
26. Resnick MB, Gueorguieva RV, Carter RL, Ariet M, Sun Y, Roth J, et al. The impact of low birth weight, perinatal conditions, and sociodemographic factors on educational outcome in kindergarten. Pediatrics 1999;104(6):e74. [PubMed: 10586008]
27. Ritz B, Yu F, Chapa G, Fruin S. Effect of Air Pollution on Preterm Birth among Children Born in Southern California between 1989 and 1993 . Epidemiology 2000;11(5):502–511. [PubMed: 10955401]
28. NRC. Research Priorities for airborne Particulate Matter, IV: Continuing Research Progress. National Academy Press; Washington, DC: 2004.
29. Hansen CA, Barnett AG, Pritchard G. The Effect of Ambient Air Pollution during Early Pregnancy on Fetal Ultrasonic Measurements during Mid-Pregnancy . Environ Health Perspect 2008;116(3): 362–369. [PubMed: 18335104]
30. Jerrett M, Arain A, Kanaroglou P, Beckerman B, Potoglou D, Sahsuvaroglu T, et al. A review and evaluation of intraurban air pollution exposure models . J Expo Anal Environ Epidemiol 2005;15(2): 185–204. [PubMed: 15292906]
31. Thomas D, Stram D, Dwyer J. Exposure Measurement Error: Influence on Exposure-Disease Relationships and Methods of Correction . Annu Rev Public Health 1993;14:69–93. [PubMed: 8323607]
32. Dominici F, Sheppard L, Clyde M. Health Effects of Air Pollution: A Statistical Review . International Statistical Review 2003;71(2):243–276.
33. Dockery DW, Pope CA, Xu X, Spengler JD, Ware JH, Fay ME, et al. An association between air pollution and mortality in six U.S cities. N Engl J Med 1993;329(24):1754–1759.
34. Samet JM, Dominici F, Curriero FC, Coursac I, Zeger SL. Fine particulate air pollution and mortality in 20 US cities, 1987–1994 . N Engl J Med 2000;343:1742–1749. [PubMed: 11114312]
35. Pope AC III, Burnett RT, Thun M, Calle EE, Krewski D, Ito K, et al. Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution . Journal of the American Medical Association 2002;287(9):1132–1141. [PubMed: 11879110]
36. Rogers JF, Dunlop AL. Air Pollution and Very Low Birth Weight Infants: A Target Population? Pediatrics 2006;118(1):156–164. [PubMed: 16818561]
37. Yang C-Y, Tseng Y-T, Chang C-C. Effects of Air Pollution on Birth Weight Among Children Born Between 1995 and 1997 in Kaohsiung, Taiwan. J Toxicol Environ Health 2003;66:807–816. Part A.
38. Ritz B, Wilhelm M, Zhao Y. Air Pollution and Infant Death in Southern California, 1989–2000 . Pediatrics 2006;118:493–502. [PubMed: 16882800]
39. Mannes T, Jalaludin B, Morgan G, Lincoln D, Sheppeard V, Corbett S. Impact of ambient air pollution on birth weight in Sydney, Australia . Occup Environ Med 2005;62(8):524–530. [PubMed: 16046604]
40. U.S. Environmental Protection Agency. Air Quality System. 2006a. http://www.epa.gov/ttn/airs/airsaqs/detaildata/downloadaqsdata.htm

41. Glinianaia SV, Rankin J, Bell R, Pless-Mulloli T, Howel D. Particulate air pollution and fetal health a systematic review of the epidemiologic evidence . Epidemiology 2004;15(1):36–45. [PubMed: 14712145]
42. Maisonet M, Bush TJ, Correa A, Jaakkola JK. Relation between Ambient Air Pollution and Low Birth Weight in the Northeastern United States . Environ Health Perspect 2001;109(3):351–356. [PubMed: 11427384]
43. Salam MT, Millstein J, Li YF, Lurmann FW, Margolis HG, Gilliland FD. Birth outcomes and prenatal exposure to ozone, carbon monoxide, and particulate matter: results from the Children's Health Study . Environ Health Perspect 2005;113(11):1638–1644. [PubMed: 16263524]
44. Liu S, Krewski D, Shi Y, Chen Y, Burnett RT. Association between Gaseous Ambient Air Pollutants and Adverse Pregnancy Outcomes in Vancouver, Canada . Environ Health Perspect 2003;111(14): 1773–1778. [PubMed: 14594630]
45. Maroziene L, Grazuleviciene R. Maternal exposure to low-level air pollution and pregnancy outcomes: a population-based study . Environ Health 2002;1(1):6. [PubMed: 12495448]
46. Basu R, Woodruff TJ, Parker JD, Saulnier L, Schoendorf KC. Comparing exposure metrics in the relationship between $PM_{2.5}$ and birth weight in California. Journal of Exposure Analysis & Environmental Epidemiology 2004;14(5):391–396. [PubMed: 15361898]
47. Gouveia N, Bremner SA, Novaes HMD. Association between ambient air pollution and birth weight in Sao Paulo, Brazil . J Epidemiol Community Health 2004;58(1):11–17. [PubMed: 14684720]
48. Parker JD, Woodruff TJ, Basu R, Schoendorf KC. Air Pollution and Birth Weight Among Term Infants in California . Pediatrics 2005;115(1):121–128. [PubMed: 15629991]
49. Myers, E.; McCrory, D.; Mills, A.; Price, T.; Swamy, G.; Tantibhedhyangkul, J., et al. Evidence Report/Technology Assessment No. 167. Rockville, MD: Agency for Healthcare Research and Quality; 2008. Effectiveness of Assisted Reproductive Technology.
50. U.S. Environmental Protection Agency. Clean Air Scientific Advisory Committee Recommendations Concerning the Final Ambient Air Quality Standards for Particulate Matter (EPA-CASCA-LTR-06-03). 2006b
51. U.S. Environmental Protection Agency. Research Triangle Park, NC. 2004. Air Quality Criteria for Particulate Matter. EPA/600/P-99/002aF

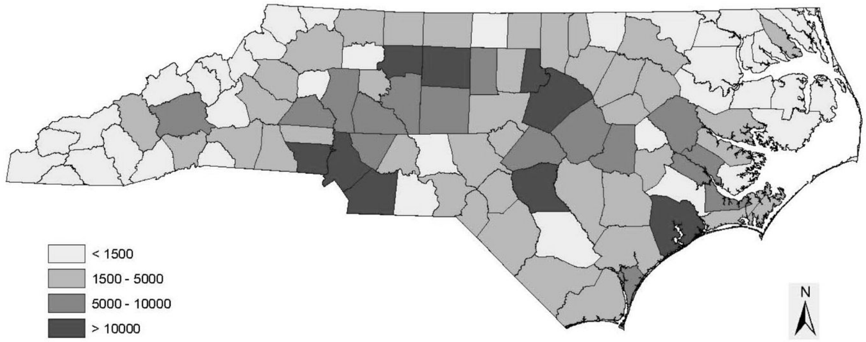


Figure 1.
Total geo-coded births in North Carolina

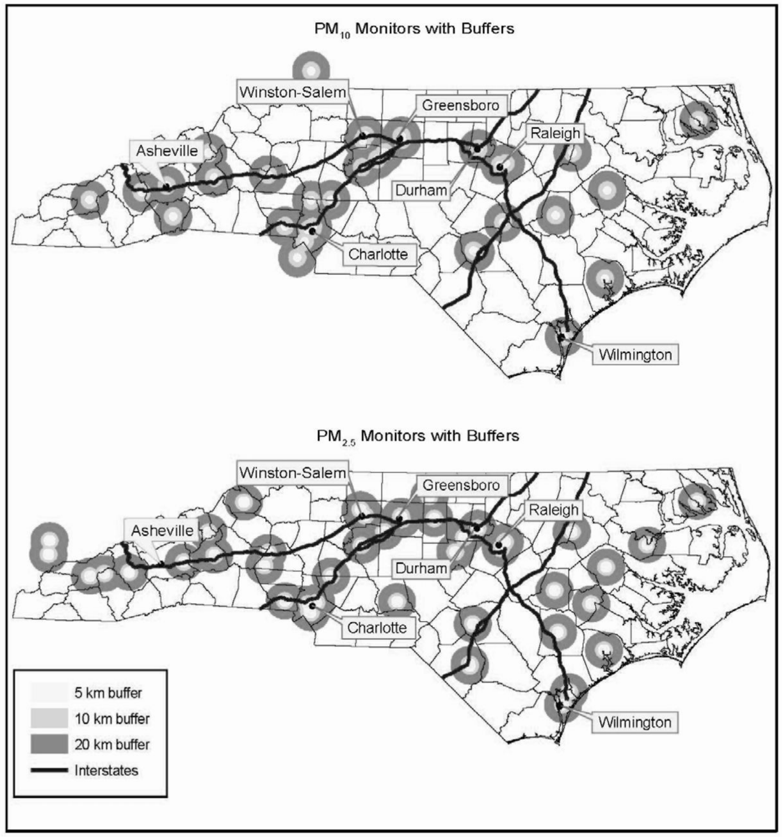
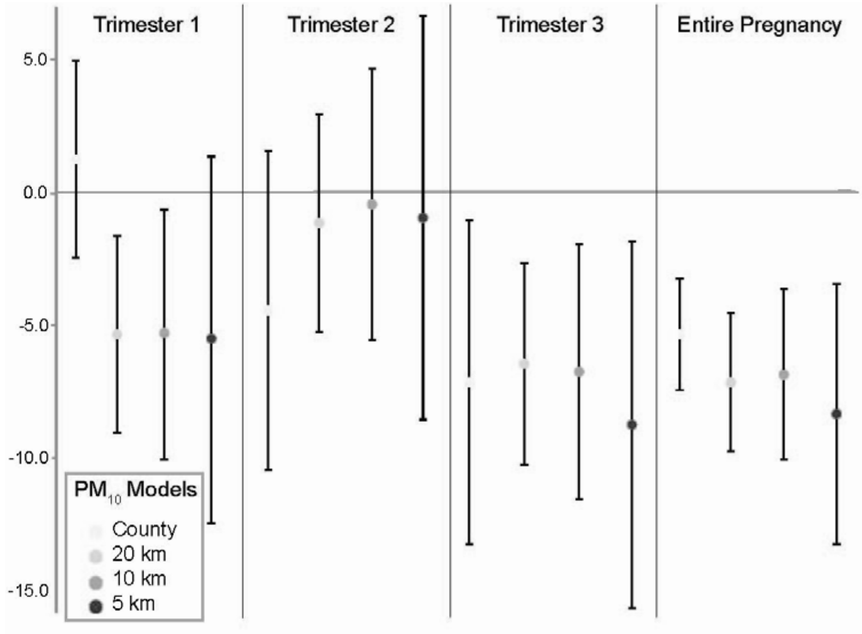


Figure 2.
Location of PM_{10} and $PM_{2.5}$ monitors and distance buffers



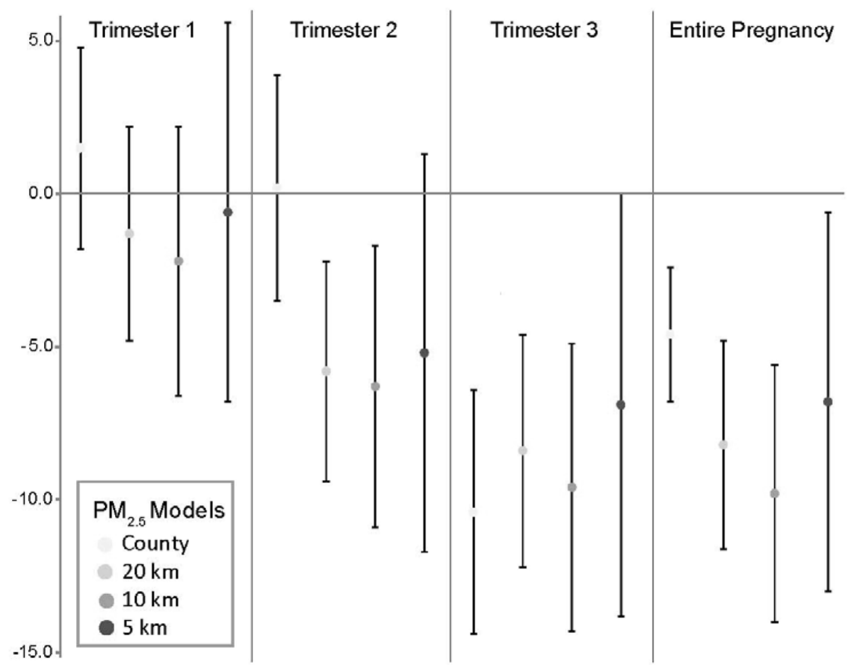


Figure 3.

Changes in birthweight in the PM models

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Table 1

Summary statistics of the study population with exposure estimates for either PM_{10} or $PM_{2.5}$

	20 km	10 km	5 km	County
Total births	167,851	110,555	56,043	195,141
Mean BWT (g) ± SD	3372 ± 528.4	3353 ± 530.5	3321 ± 531.9	3368 ± 530.9
% LBW	5.2	5.6	6.3	5.4
Mean Gestation (weeks) ± SD	38.9 ± 1.6	38.9 ± 1.6	38.9 ± 1.7	38.9 ± 1.6
32–34 (%)	2.0	2.2	2.3	2.2
35–36 (%)	5.5	5.6	6.0	5.7
37–38 (%)	24.9	25.0	25.1	24.6
39–40 (%)	54.8	54.4	54.0	54.7
41–42 (%)	11.3	11.4	11.1	11.4
43–44 (%)	1.4	1.4	1.5	1.4
% Male	50.9	51.0	50.7	51.0
% Firstborn	42.8	43.3	42.3	42.9
% Trimester				
Prenatal Care				
1st	86.2	84.6	81.2	86.0
2nd	10.8	12.0	14.6	11.0
3rd	1.7	2.0	2.5	1.7
none	0.7	0.9	1.2	0.8
Unknown	0.6	0.5	0.5	0.5
% Race/Ethnicity				
NHW	61.7	52.9	41.9	61.1
NHB	25.7	32.2	39.4	26.1
HISP	12.6	14.9	18.8	12.8
% Maternal Education (years)				
< 9	5.5	6.6	9.0	5.7
9–11	13.8	15.1	19.2	13.9
12	27.5	28.0	29.3	27.7
13–15	22.3	21.5	19.5	22.3
> 15	31.0	28.8	23.0	30.5
%Maternal Age (years)				
15–19	10.6	11.6	13.9	10.8
20–24	25.4	27.4	30.3	25.7
25–29	26.8	26.3	25.2	26.9
30–34	24.7	23.0	20.1	24.4
35–39	10.7	9.9	8.9	10.5
40–44	1.8	1.7	1.6	1.8
%Tobacco Use	11.2	10.7	11.4	10.9
%Married	68.4	63.1	54.0	68.2

Table 2

Pollutant averages ± SD and IQR of pollutants by pregnancy period

Exposure Period	Pollutant	County Level PM$_{10}$ (n=178,356) PM$_{2.5}$ (n=174,933) Mean ± SD	IQR	Quartiles 25%	50%	75%	20 km PM$_{10}$ (n=117,279) PM$_{2.5}$ (n=134,232) Mean ± SD	IQR	Quartiles 25%	50%	75%
Trimester 1	PM$_{10}$	19.6 ± 5.5	5.5	16.2	17.8	21.8	23.0 ± 5.4	7.2	19.0	22.5	26.2
	PM$_{2.5}$	13.5 ± 1.5	1.9	12.5	13.7	14.3	15.0 ± 3.0	4.2	12.7	12.5	16.8
Trimester 2	PM$_{10}$	25.1 ± 5.3	7.3	21.0	24.3	28.3	22.6 ± 4.9	6.6	19.1	22.4	25.6
	PM$_{2.5}$	15.3 ± 1.7	2.1	14.5	15.6	16.6	14.4 ± 2.6	3.9	12.7	14.4	16.7
Trimester 3	PM$_{10}$	26.5 ± 5.2	7.9	22.6	25.7	30.5	22.4 ± 4.9	6.4	19.0	22.3	25.4
	PM$_{2.5}$	18.2 ± 2.8	3.1	16.8	18.3	19.9	14.6 ± 2.6	3.9	12.3	14.3	16.5
Entire Pregnancy	PM$_{10}$	23.7 ± 4.9	4.8	20.7	22.7	25.5	22.6 ± 3.8	3.8	20.5	22.2	24.3
	PM$_{2.5}$	15.7 ± 1.6	1.6	15.0	15.7	16.6	14.7 ± 1.7	2.2	13.7	14.9	15.9

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Table 3

Pearson correlation coefficients for between trimester pollutions estimates at the county level

		PM_{10}					$PM_{2.5}$		
		T1	**T2**	**T3**			**T1**	**T2**	**T3**
	T1	1				T1	1		
PM_{10}	T2	0.44	1		$PM_{2.5}$	T2	0.23	1	
	T3	0.16	0.42	1		T3	−0.08	0.24	1

Table 4

Change in birthweight in the baseline models for PM_{10}

	County PM_{10}	**20 km PM_{10}**
Male Sex	127.3 (123.4 to 131.1)	126.4 (107.1 to 145.8)
Mat Edu (years)		
< 9	−40.2 (−50.4 to −29.9)	−41.1 (−54.5 to −27.8)
9–11	−33.9 (−40.3 to −27.5)	−39.6 (−47.0 to −32.2)
12		
13–15	22.8 (17.1 to 28.5)	18.5 (11.9 to 25.1)
> 15	24.6 (18.6 to 30.6)	21.9 (15.0 to 28.9)
Maternal tobacco Use	−188.5 (−195.2 to −181.9)	−194.7 (−202.6 to −186.9)
Maternal Race/Ethnicity		
NHW		
NHB	−179.2 (−184.3 to −174.1)	−178.8 (−184.6 to −172.9)
HISP	−70.5 (−77.5 to −63.7)	−75.6 (−83.4 to −67.8)
Trimester of Prenatal Care		
1st		
2nd	−11.4 (−17.9 to −4.9)	−11.6 (−19.3 to −3.9)
3rd	−35.2 (−50.1 to −20.3)	−18.1 (−36.0 to −0.1)
No care	−19.1 (−41.8 to 3.5)	−29.7 (−56.8 to −2.61)
Maternal Age in years		
15–19	−42.6 (−51.5 to −33.7)	−40.8 (−51.2 to −30.5)
20–24	−31.5 (−37.8 to −25.2)	−32.7 (−40.0 to −25.5)
25–29	−7.1 (−12.6 to −1.5)	−6.9 (−13.2 to −0.5)
30–34		
35–39	−2.8 (−9.9 to 4.4)	−3.7 (−12.0 to 4.6)
40–44	−34.9 (−49.8 to −19.9)	−28.5 (−45.6 to −11.3)
Firstborn Non Gestational length (weeks)	114.4 (110.2 to 118.7)	115.1 (110.1 to 120.1)
32–34	−1285.1 (−1298.6 to −1271.7)	−1287.8 (−1303.9 to −1271.7)
35–36	−714.5 (−723.1 to −705.9)	−714.3 (−724.3 to −704.3)
37–38	−278.5 (−283.2 to −273.8)	−278.2 (−283.6 to −272.8)
39–40		
41–42	186.8 (180.5 to 193.1)	185.8 (178.5 to 193.1)
43–44	256.7 (240.4 to 273.0)	240.5 (221.1 to 259.8)